HIGH ENERGY EMISSION FROM MICROQUASARS

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Abstract The microquasar phenomenon is associated with the production of jets by X-ray binaries and, as such, may be associated with the majority of such systems. In this chapter we briefly outline the associations, definite, probable, possible, and speculative, between such jets and X-ray, γ-ray and particle emission.

Introduction: what is a microquasar ?

The answer to the above question depends somewhat on your viewpoint, but ours is the following: a 'microquasar' is an X-ray binary (XRB) which produces jets. Figure 1 is a sketch of an XRB, presenting the major physical components and sites of emission in such systems. Currently about 250 XRBs are known in our galaxy (comprehensively catalogued in Liu, van Paradijs & van den Heuvel 2000, 2001), possibly representing an underlying population of $\geq$ 1000 objects, depending on the value of any low-luminosity cut off to the distribution (e.g. Grimm, Gilfanov & Sunyaev 2002).

Figure 2 presents the spatial distribution of known XRBs: these can be separated into two populations: the low-mass XRBs (where 'low mass' refers to the binary companion star) which are believed to be older, and are concentrated near the Galactic bulge, and the younger high-mass XRBs concentrated in the spiral arms. In general, the low mass X-ray binaries transfer mass to their companions through Roche lobe overflow, while the high mass X-ray binaries transfer mass through strong stellar winds. For the purposes of jet formation the mass transfer mechanism does not seem to be important, and we can consider Fig 2 as demonstrating the roughly uniform distribution of XRBs with mass in the galaxy.

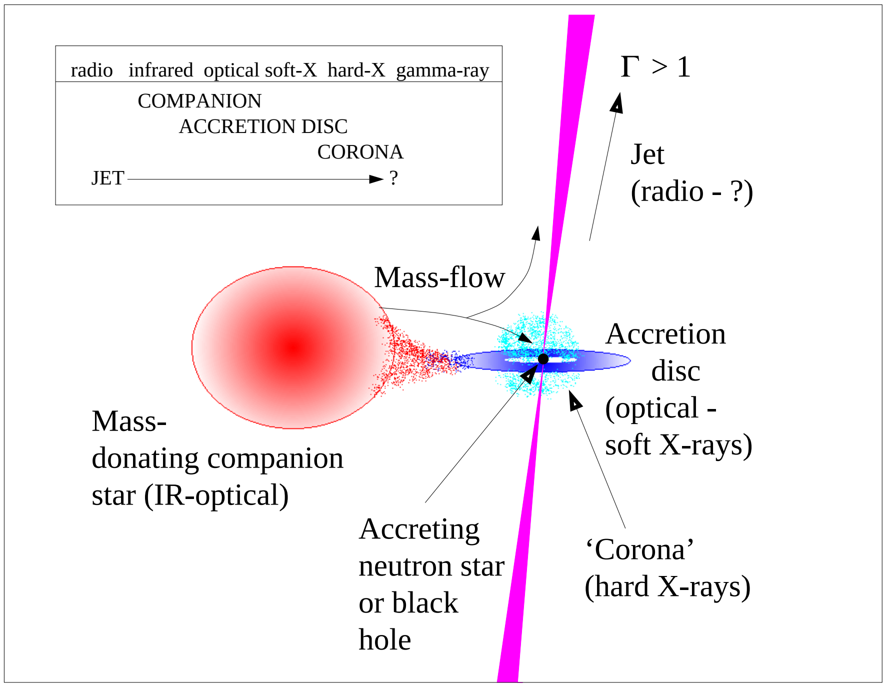

Figure 1. Sketch illustrating our current concept of the physical components and sites of emission in an X-ray binary system. A compact object (neutron star or black hole) accretes material from a binary companion, and the potential accretion energy is released in the form of a combination of high-energy emission (UV / X-rays / γ-rays) and mechanical energy in an outflow (which itself may be the site of some high-energy emission).

Based on our definition of a microquasar, about 15% of the Milky Way's X-ray binaries (including nearly all of its X-ray binaries thought to contain a black hole) definitely fall into this class. However, in our opinion, jet production is in fact likely to be common for up to 70% of X-ray binaries (see arguments in Fender 2004). In this case it is perhaps more appropriate to consider 'microquasar' as a *phenomenon* associated with XRBs, rather than considering microquasars to be some unusual subset of objects.

The jets from XRBs appear to come in two types. Firstly, in 'hard' X-ray states – typically observed for bolometric X-ray luminosities $\leq 5\%$ Eddington (Maccarone 2003) – a steady, self-absorbed outflow appears to be ubiquitous in both black hole (BH; e.g. Fender 2001) and neutron star (NS; Migliari et al. 2003a) XRBs. These jets appear to be self-absorbed (based upon their flat or inverted radio spectra: corresponding to spectral index $\alpha \geq 0$ where the relation between flux density and

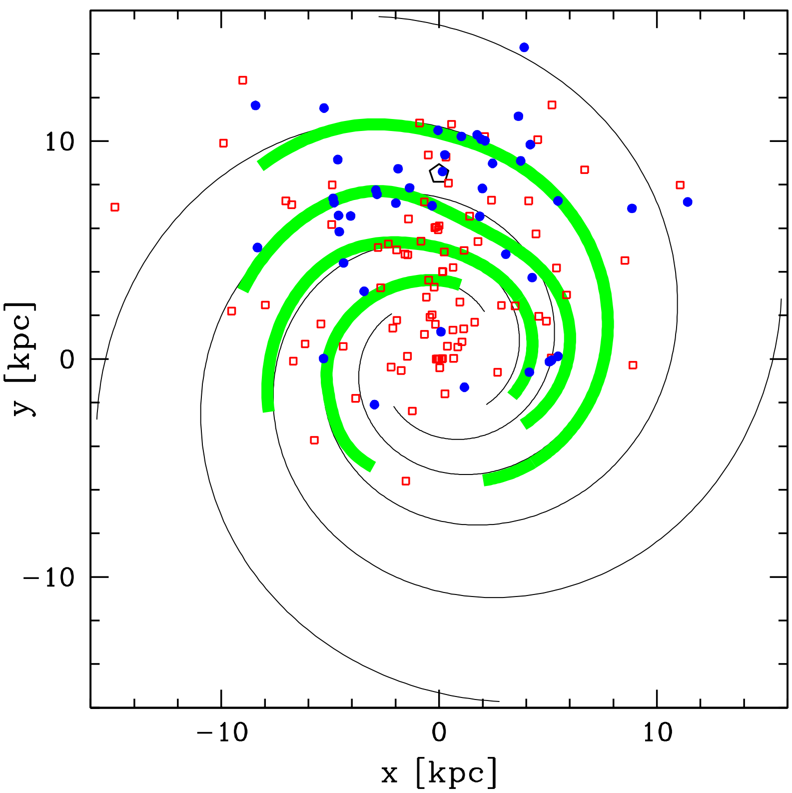

Figure 2. The relatively uniform distribution of known XRBs within our galaxy. The Sun is located at (0,8.5). From Grimm et al. (2002).

frequency is given by $S_\nu \propto \nu^\alpha$). They are also strongly coupled to the X-ray emission from these systems, evident in an apparently universal correlation between radio and X-ray luminosities of the form

$$L_{\rm radio} \propto L_{\rm X}^b$$

where $b \sim 0.7$ (Corbel et al. 2003; Gallo, Fender & Pooley 2003). Based on the limited scatter around a single function of this form, Gallo, Fender & Pooley (2003) concluded that the bulk Lorentz factor ($\Gamma = [1-\beta^2]^{0.5}$, where the velocity $v = \beta c$) is probably less than 2.

At slightly higher X-ray luminosities, the X-ray spectra of XRBs softens. In the 'high/soft' states of BH XRBs the radio emission is dramatically 'quenched', probably indicating suppression of jet formation (Tananbaum et al. 1972; Fender et al. 1999; Gallo, Fender & Pooley 2003). There is a hint that similar behaviour may be exhibited by NS

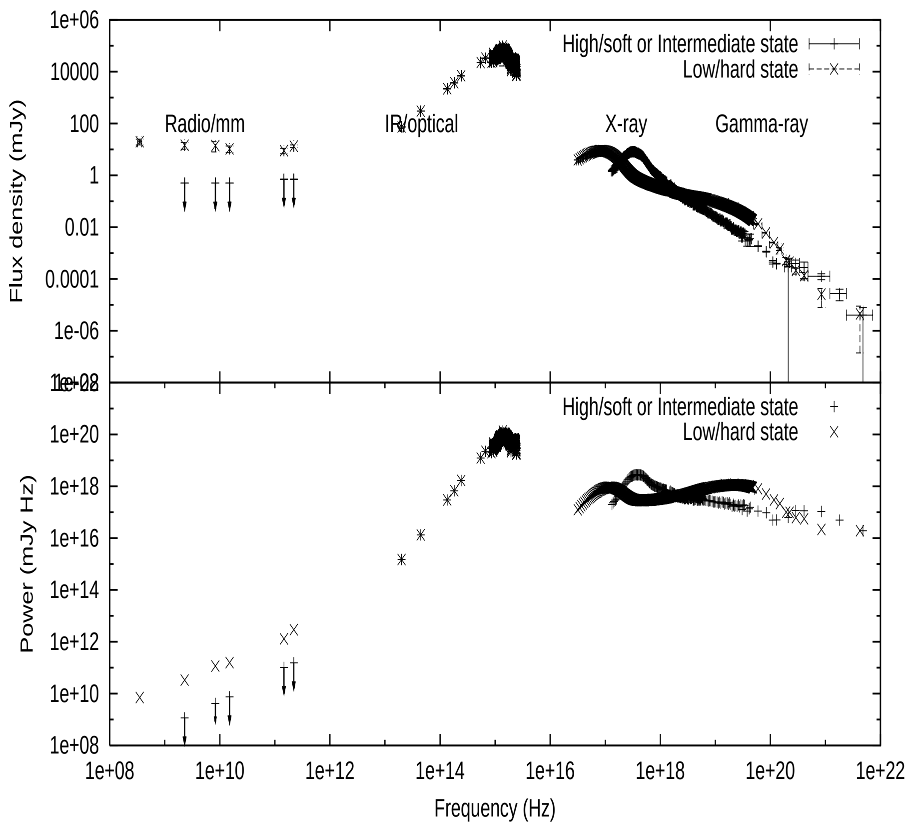

Figure 3. Broadband spectra – over 14 decades in frequency – of Cygnus X-1 in the 'low/hard' and softer ('high/soft' or 'intermediate') states, in flux density and spectral power representations. The radio–mm emission is significantly stronger in the 'low/hard' state, which has an X-ray spectrum which peaks in power at ~ 100 keV. The infrared–optical regime is dominated by the OB companion star, whose emission (of course) does not change between states. Note that despite the significantly altered radio and X-ray spectra, γ-ray detections at ≥ 1 MeV are comparable in both X-ray states. From Tigelaar et al. (2003).

XRBs (Migliari et al. 2003). At higher luminosities (but see Homan et al. 2001) the 'intermediate' or 'very high' state of BHs – *or the rapid transition to this state* – is associated with the formation of discrete, powerful jets. These jets are likely to have bulk Lorentz factors $\Gamma > 2$ and so are different to the steady jets in the low/hard state (for further discussion see Fender 2004). At the highest luminosities NS XRBs

also display powerful, highly relativistic jets (e.g. Fomalont et al. 2001; Fender et al. 2003). Overall the BH and NS XRBs appear to show analogous patterns of jet formation as a function of (apparent) bolometric luminosity, although the NS XRBs are a factor 10–100 less 'radio loud' than the BH XRBs (Fender & Kuulkers 2001; Migliari et al. 2003).

The high/soft state is generally thought to be dominated by a geometrically thin, optically thick accretion disk (e.g. Shakura & Sunyaev 1973). As such, it may be incapable of extracting rotational energy efficiently, either from itself or from the central black hole (e.g. Livio, Ogilvie & Pringle 1999; Meier 2001; Livio, King & Pringle 2003), as thin disks are expected to have weaker poloidal magnetic fields than thick disks. That Galactic black holes, neutron stars, and more recently, active galactic nuclei (Maccarone, Gallo & Fender 2003) all show suppression of jet formation in the $\sim$2-10% of Eddington luminosity range where high/soft states are seen bolsters the case for this theoretical picture.

Figure 3 demonstrates the broad band spectra of hard and soft X-ray states in the BH XRB Cygnus X-1, clearly indicating the 'quenching' of the radio and mm emission in the 'soft' X-ray state. In the context of this chapter it is interesting to note that the source is detected at MeV energies in both states (see McConnell et al. 2002 for a more detailed discussion).

X-ray emission from jets ?

In the following section we shall discuss the observational evidence and theoretical interpretations / speculations regarding the emission of X-rays from the two types of XRB jets outlined above.

X-rays from steady jets ?

It should be stated from the start that there is no direct evidence that the steady jets associated with hard X-ray states are the sites of any of the observed X-ray emission. What is clear is that there is a strong coupling between radio and X-ray luminosities (as noted above), and that this therefore implies a strong coupling between the jet and accretion flow. Figure 3 demonstrates the dramatic change in the radio–mm component of the spectrum of a BH XRB (Cygnus X-1) correlated with changes in the X-ray spectrum. Note that in the low/hard state of this source a jet has been directly imaged with radio VLBI (Stirling et al. 2001). Figure 4 shows the spectrum of the powerful XRB jet source GRS 1915+105 in a 'plateau' state (the nearest it gets to the 'standard' low/hard state), together with radio VLBI images made contempora-

neously which reveal a steady compact jet. It is clear that when such steady jets are present there are a lot of hard X-rays. It is possible that this X-ray component *does* originate in the base of the jet, via optically thin synchrotron emission (e.g. Markoff, Falcke & Fender 2001) but this is not the widely accepted interpretation, which is instead that the X-rays arise via Comptonisation of softer photons in a hot ($\sim$ 100 keV) plasma (e.g. Thorne & Price 1975; Zdziarksi et al. 2003).

X-rays from transient relativistic jets ?

This question is much easier to answer, with an unambigous *yes*. Figure 5 presents *Chandra* X-ray images of moving large-scale jets from the transient BH XRB XTE J1550-564, two years after a major outburst (Corbel et al. 2002; Kaaret et al. 2003; Tomsick et al. 2003; see also Wang, Dai & Lu 2003). While XTE J1550-564 was very bright, there was nothing outstandingly unusual about it, and so we may conclude that large-scale X-ray emitting jets are probably rather commonly associated with XRB outbursts. The radio-through-X-ray spectrum of these moving jets can be fit by a single power law with spectral index $\alpha = -0.660 \pm 0.005$, entirely consistent with optically thin synchrotron emission. Applying minimum energy arguments (see e.g. Longair 1994), we can derive a magnetic field in the jets of 0.3mG. This in turn implies that the leptons emitting in the soft X-ray band have been accelerated to TeV energies, presumably by an interchange of bulk kinetic energy to particles via shocks. Large-scale X-ray jets are also associated with the unusual X-ray binary SS 433 (Brinkmann, Aschenbach & Kawai 1996; Migliari, Fender & Mendez 2002) and the transient 4U 1755-33 (Angelini & White 2003). We also note that extended jets represent an additional possible mechanism for producing the elongated X-ray sources seen in deep Chandra images of the Galactic Center region, previously suggested to be predominantly pulsar wind nebulae (Lu, Wang & Lang 2003).

High-energy γ-ray emission

For the purposes of this chapter, we refer to any γ-rays above 30 MeV as high energy (HE) γ-rays, and γ-rays above 100 GeV as VHE γ-rays. In this way, HE γ-rays are restricted to be photons which nearly all models have associated with some kind of high velocity relativistic shocks, generally in a jet. The VHE γ-rays are defined to be only those photons which can be detected only through ground-based γ-ray observatories. We will concentrate on the emission detected from jets here, rather than the emission from systems which are known not to have jets, such as the X-ray pulsars (for example, Cen X-3 - see Chadwick et al. 2000).

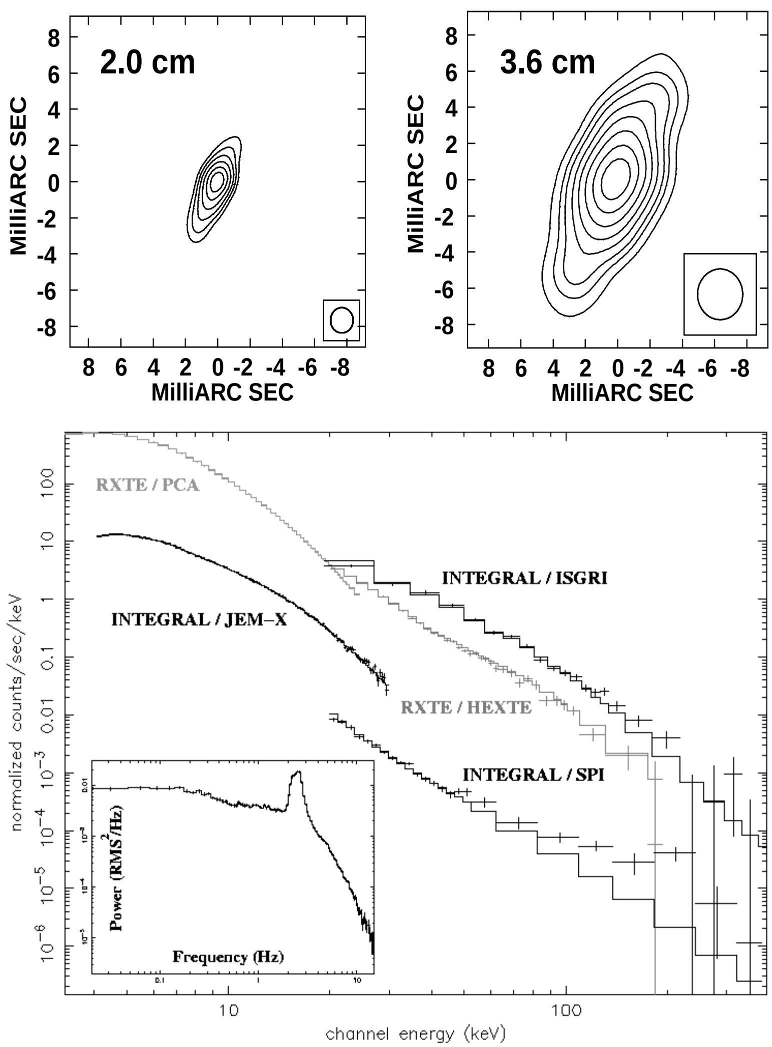

Figure 4. High-energy emission from GRS 1915+105 in a steady-jet-producing 'plateau state'. The top panel shows VLBA observations of GRS 1915+105 revealing a steady, compact, jet during a period of steady, hard X-ray emission, commonly referred to as a plateau. The lower panel shows the X-ray spectrum of the source during this period, as observed with RXTE and INTEGRAL. The inset shows the X-ray power spectrum as measured by RXTE. From Fuchs et al. (2003).

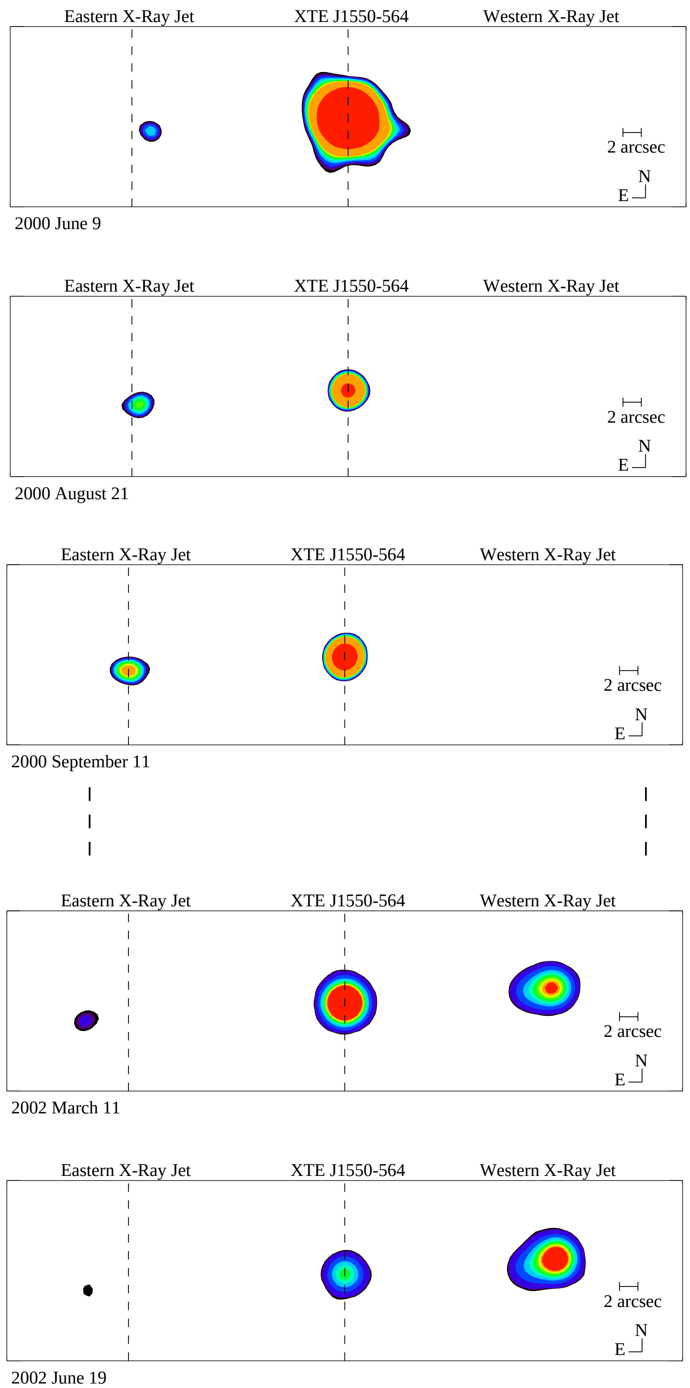

Figure 5. X-ray emission from large-scale jets produced during an outburst of the black hole transient XTE J1550564. Adapted from Corbel et al. (2002). Under minimum energy conditions, the leptons radiating in the soft X-ray band should have TeV energies.

Observations

There have been numerous claims of detection of HE γ-rays from X-ray binaries, but to date, with three that are fairly convincing. These detections have come primarily from EGRET (see Hartman et al. 1999 for the EGRET catalog, and the text below for a discussion of the individual X-ray binary jet sources), although a few detections have been claimed from the ground-based Cerenkov telescopes. There have also been suggestions that many of the EGRET unresolved sources in the Galactic plane are X-ray binaries (e.g. Kaufman Bernadó, Romero & Mirabel 2002) or other accreting stellar mass compact objects with jets (e.g. Armitage & Natarajan 1999; Punsly et al. 2000).

Cygnus X-3 The first X-ray binary with jets suggested to emit TeV $\gamma-$rays is Cygnus X-3 (Samorski & Stamm 1983; Chadwick et al. 1985). The detection is bolstered by the fact that the TeV $\gamma-$rays are strongest during the X-ray maxima in the 4.8 hour orbital period (Chadwick et al. 1985). Other groups have failed to detect Cygnus X-3 during the X-ray maximum (e.g. O'Flaherty et al. 1992), but this may be a result of variability.

Additionally, a 12.6 msec periodicity has been reported by multiple groups, although the period measurements are quite precise and seem not to be exactly consistent with one another (Chadwick et al. 1985; Brazier et al. 1990; Gregory et al. 1990). On the other hand, these pulse periods are based on rather small numbers of photons. Furthermore, the statistical singificance of the pulse detection has been debated on the ground that the calculations of the signficance level have ignored the DC component of the emission (Protheroe 1994).

The association of the periodicity with an actual pulsar (i.e. a rotating neutron star) is a bit more troubling. Firstly, jets have been observed from Cygnus X-3 (in fact, the brightest radio jets of any X-ray binary in the Galaxy), but have not been observed from any other accreting X-ray pulsar; it is believed that the strong magnetic field in the X-ray pulsars may suppress jet formation (e.g. Fender & Hendry 2000). Furthermore, the fact that Cyg X-3 at its peak is has the highest ratio of radio to X-ray flux of any Galactic X-ray binary indicates that it probably contains a black hole accretor, since the neutron stars typically fall 10-100 times below the black holes in their ratios of radio to X-ray flux. Additionally, the 12.6 msec period has never been detected in other wavelengths, although this may be partly because of scattering through an extremely dense wind environment. It is believed on dy-

namical grounds that Cygnus X-3 might contain a black hole (see e.g. Schmutz et al. 1996; Hanson, Still & Fender 2000).

LS 5039 Another strong case of an X-ray binary emitting HE γ-rays can be made for LS 5039. It shows persistent radio jets with a size scale of $\sim 10^{14}$ centimeters, and is positionally coincident with an EGRET source. The γ-ray emission also seems to be persistent (Paredes et al. 2000 and references within). The very high ratio of γ-ray to radio power, in combination with the rather large size scale of the radio emitting region led Paredes et al. (2000) to suggest that that the dominant emission process is inverse Comptonization with seed photons dominated by the bright mass-donating star.

LS I +61 303 Relatively strong evidence exists for γ-ray emission from this source as well. There is a positional coincidence with the COS B and EGRET source 2 CG 135+01 (Gregory & Taylor 1978; Kniffen et al. 1997). This source is highly variable in the radio and X-ray bands, as it is a B[e] accreting binary with a highly eccentric orbit. However, the $\gamma-$rays do not show any clear sign of variability, let alone variability correlated with that in the radio (Kniffen et al. 1997). Still, there are no other strong candidate sources within the EGRET error boxes.

Unidentified EGRET sources in the galactic plane Almost half of the unidentified EGRET sources are within 10 degrees of the Galactic plane (Hartmann et al. 1999), so it seems likely that a large fraction of the sources are Galactic in origin. While recent follow-ups suggest that some of the previously unidentified sources may be young pulsars (Halpern et al. 2001; D'Amico et al. 2001; Torres et al. 2001), the spatial distribution seems more consistent with that of molecular clouds (e.g. Bhattacharya et al. 2003), and the follow-up of LS 5039 as the counterpart of a previously unidentified EGRET source suggests that at least some fraction of these sources may be X-ray binaries.

Predictions

Numerous models make different predictions for the VHE γ-ray production. Below we discuss these models briefly.

Synchrotron self-Comptonization models

The simplest mechanism invoked for explaining the VHE gamma-rays seen in blazars are those which invoke synchrotron self-Compton radiation. In such a model, the same electrons produce two broad peaks

in the spectrum. A low energy peak comes from synchrotron radiation, and a higher energy peak comes from Compton upscattering (e.g. Jones, O'Dell & Stein 1974). The photon energies of the two peaks depend on the electron energy distribution and on the magnetic field. The ratio of the luminosity of synchrotron component to the luminosity of the Compton component is equal to the ratio of the magnetic energy density to the photon energy density.

A recent set of models has suggested that in some X-ray binaries, the hard X-rays may be dominated by synchrotron emission from a relativistic jet. Two strong examples are XTE J1118+480 (Markoff, Falcke & Fender 2001) and GX 339-4 (Markoff et al. 2003), although in this general framework some other sources show X-ray emission dominated by the Compton component of the jet. Since the TeV blazars all have X-ray emission dominated by synchrotron emission from the jet, these seem to be ideal candidates for observing TeV emission from an X-ray binary. In fact, for the case of GX 339-4, the synchrotron self-Compton spectrum has been presented for the fit to the brightest low/hard state for which there is good multi-wavelength data; the predicted γ-ray fluxes are below the sensitivity of $\sim$ few MeV instruments such as those aboard INTEGRAL, but above the detection limits anticipated from GLAST, and near the one night detection limits for STACEE and HESS (see Figure 6, reproduced from Markoff et al. 2003). The magnetic field predicted for X-ray binaries may be higher than that inferred for blazars, which means that despite the fact that the hard X-rays from GX 339-4 extend to energies seen only in Mkn 501 in the blazars, the electron energies and hence the highest energies of the Compton scattered photons are a factor of about 100 lower than seen in Mkn 501.

External Comptonization models

The next step up in complication from the synchrotron self Comptonization models is external Comptonization. In such a picture, there is an additional source of seed photons to the Comptonizing region aside from the synchrotron photons. In the context of AGN, this additional source of photons is often assumed to be the accretion disk (Dermer & Schlickeiser 1993) or the broad line region (e.g. Sikora, Begelman & Rees 1994). The broad line region is usually located not too far from the active region of the jet, and it is further from the central engine than is the active region of the jet, so the jet's motions will be toward the BLR.

In the context of X-ray binaries, a possible important source of external photons is the mass donating star. External Comptonization in the relativistic jet has been suggested to explain the hard tail seen by

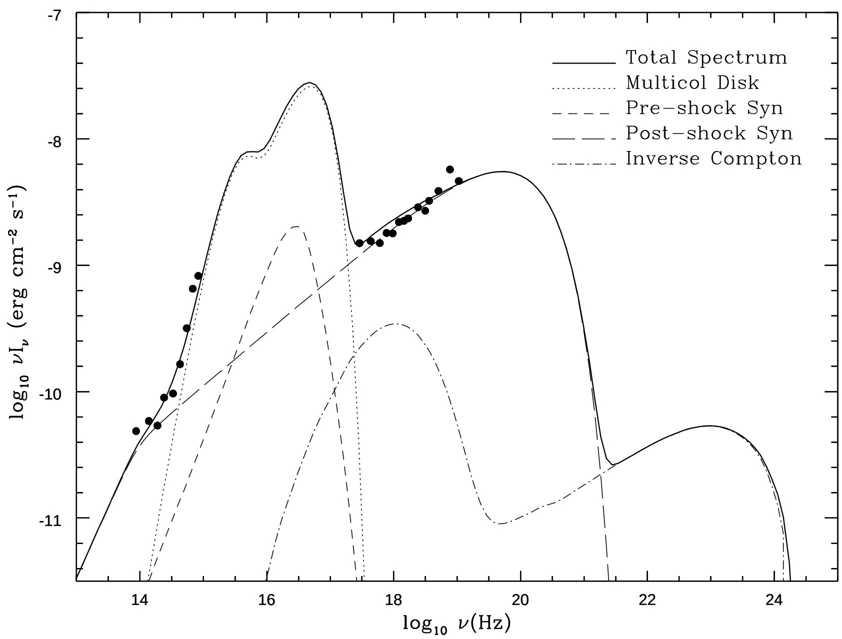

Figure 6. Figure 3 (adapted from Markoff et al. 2003), which shows the jet model fits to the 1981 radio-through-X-ray data for the bright low/hard state of GX 339-4 and predictions for the inverse Compton emission from this model.

COMPTEL (McConnell et al. 2002) for Cygnus X-1 (Georganopoulos, Aharonian & Kirk 2002; Romero, Kaufman Bernado & Mirabel 2002). It has also been suggested as an explanation for the possible association of LS 5039 with an EGRET source. In both cases, the mass donor is a high mass star; for the low mass X-ray binaries, the photon fields of the donors are likely to be too weak to provide significant seed photon populations. It may also be that external Comptonization will be more important if the jet is not perpendicular to the binary's orbital plane; this seems to be the case whenever good measurements of both the jet and orbital plane inclination angles are measurable, and seems to be especially likely to occur for high mass X-ray binaries which have short system lifetimes and hence cannot change the spin axis of the mass accretor (Maccarone 2002). A particularly promising candidate for this misalignment effect is V4641 Sgr, which has an extremely strong misalignment, and also is a microblazar (see e.g. Orosz et al. 2001). Attempts to fit jet models incorporating the external photons fields from the accretion disc and from the companion star are underway (Markoff & Maccarone, in prep).

In general, there are two key effects of external Comptonization. The first is that the ratio of luminosity in the Compton component to that in the synchrotron component is boosted, since $L_{synch}/L_{Compt} = U_B/Uph$ (see e.g. Rybicki & Lightman 1979). The second is that the cooling rate is boosted by the addition of the additional soft photons, pushing the Compton and synchrotron peaks to lower energies. Evidence of this phenomenom in AGN is probably seen. The brightest blazars presumably have the accretion disks and broad line regions which contribute the most flux. They also have the most $\gamma-$ray dominant spectra and the lowest peak energies for both the synchrotron and Compton components of the spectrum (e.g. Fossati et al. 1998 - see Figure 7). It is also noted that a pure synchrotron self-Comptonization scenario could also explain the observed correlations if there is a systematic variation in magnetic field strengths, with the brightest blazars have the weakest magnetic fields (Fossati et al. 1998). This may have important implications for detecting $\gamma-$ray emission from X-ray binaries, as well.

Hadronic jet models

The three putative HE/VHE γ-ray sources among the X-ray binaries are all high mass X-ray binaries with strong stellar winds in addition to the strong photon fields. Given that there will be dense matter fields in the region where the jet exists, there should also be strong collisions between the jet and the matter from the stellar wind. The collisions will lead to pion decays, and hence to the production of γ-rays and neutrinos (Romero et al. 2003). A potential problem with this model is that the jets may be pair dominated in the low Eddington fraction steady jet systems such as LS 5039 by analogy with AGN. There is some evidence that the FR I jets which are analogous to the low/hard state steady jets (Meier 1999; Maccarone, Gallo & Fender 2003) may be pair dominated (e.g. Reynolds et al. 1996); if confirmed, then this model would be ruled out. The strong neutrino flux predictions may be testable even sooner.

Gamma-ray lines

For the most part, γ-ray lines have been seen from diffuse sources where nuclear reactions are occuring, rather than from point sources. However, there is at least one instance of a measurement of a γ-ray line from an X-ray binary - that seen in Nova Mus 1991, at 481$\pm$22 keV (Gilfanov et al. 1991). Two possible interpretations of this emission line have been suggested - redshifted annihilation, possibly from a recombination of pairs in a pair-dominated relativistic jet (e.g. Kaiser & Hannikainen 2002) or a ^{7}Li re-combination line at 478 keV, possibly re-

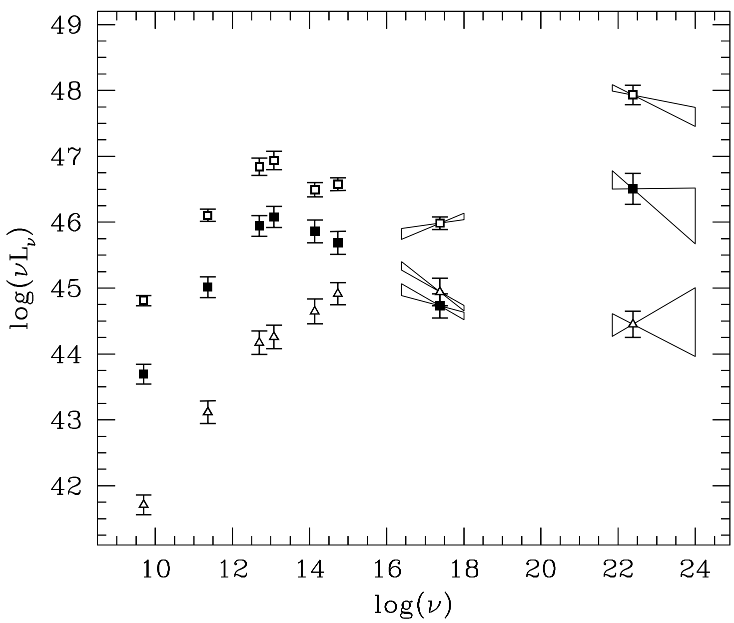

Figure 7. Figure 10 from Fossati et al. 1998, which shows how blazars shift to lower energy peaks with higher fractions of their total power in the Compton component at higher luminosities. The open boxes represent flat spectrum radio quasars (the brightest sources), the filled boxes represent the 1 Jy BL Lac sample (intermediate brightness sources), and the traingles represent a fainter sample of BL Lac objects. Note also, the similarity with Figure 6, apart from the accretion disk's contribution in GX 339-4, which is relatively stronger than in the blazars because the jet is not beamed towards the observer in GX 339-4.

lated to a collision between a mis-aligned relativistic jet and the mass donor (Butt, Maccarone & Prantzos 2003). That the mass donor in Nova Mus 1991 shows a lithium excess (Martin et al. 1996) lends some support to the idea that the spectral line is a Li line. Further support may be lent by the observational and theoretical evidence for the association of jets ejected at high luminosities (like that in Nova Mus 1991) with the FR II AGN jets (Meier 1999; Maccarone, Gallo & Fender 2003). The energetics of FR II jets seem to suggest that they must be baryon dominated (Celotti & Fabian 1993). The ubiquity of lithium excesses, on the other hand is a point against the jet-star interaction scenario for producing lithium during the outbursts.

Why are there so few sources, and how do we find more?

Relatively few phenomena have been seen clearly in active galactic nuclei and not in X-ray binaries. Very high energy gamma-ray emission seems to be one of these. The question thus arises about whether this is because of a physical difference between the two types of systems or due to observational selection effects. At the present time, all the associations of high energy γ-rays with X-ray binaries remain speculative. On the other hand, there are many confirmed EGRET blazars and a handful of TeV γ-ray AGN. There are numerous possible reasons for this:

Lower radio luminosities?

One of the keys to identifying the EGRET blazars with their counterparts at other wavelengths is the presence of a strong radio source (typically above 1 Jy) within the error box. It has been shown that the ratio of radio to X-ray power for AGN is systematically much higher than for X-ray binaries due to a mass term in the fraction of the total jet power that comes out at a given radio frequency (e.g. Heinz& Sunyaev 2003; Merloni, Heinz & Di Matteo 2003; Falcke, Körding & Markoff 2003). Therefore, many of the EGRET unidentified sources may be X-ray binaries in the Milky Way which have not been associated with counterparts at other wavelengths as easily as have the high latitude EGRET sources.

Rapid variability?

It is generally believed that the variability timescales for accreting objects vary linearly with the mass, as the mass is the most important size scale for such systems. Taking as a template, for example, the

durations of the TeV flares from Mkn 421 and Mkn 501, which are typically a few months, and the estimated masses of the black holes in these systems (typically greater than $10^8 M_\odot$ - see e.g. Barth, Ho & Sargent 2003), we find that the peak γ-ray emitting time period would be of order one second or less for a 10 $M_\odot$ black hole. In reality, the situation may not be so bad; the X-ray binaries are much closer than the blazars and hence are brighter in all other wavelengths but radio. They might thus be observable far deeper in the outburst than the blazars. The real problem is likely to be one of duty cycle; the duration for which X-ray binaries emit radiation is likely to be rather short because the evolution of the outburst cycle is quite rapid. Without excellent sampling in the γ-rays over the peak of the outburst cycle, it seems unlikely that the short period where the VHE $\gamma-$rays are emitted will coincide with the observations.

Beaming requirements?

The blazars from which we have seen VHE $\gamma-$rays are all highly beamed. Given that the probability of a seeing a source with Doppler factor δ is roughly δ^{-2} and that there are only a few hundred X-ray binaries in the Milky Way, the number of highly beamed sources is quite small. There are, however, a few sources that do show strong evidence for being highly beamed - Cygnus X-3 which shows a strong jet and no counterjet on small distance scales (see e.g. Mioduszewski et al. 2001), and V4641 Sgr (Hjellming et al. 1999; Orosz et al. 2001) and Cir X-1 (Fender et al. 2003), which show proper motions corresponding to apparent velocities in excess of $15c$. Cygnus X-3 *is* one of the strongest candidates for having shown VHE γ-ray emission among the Galactic source. The outbursts of V4641 Sgr have been extremely rapid, meaning that the response time of current TeV observatories may have been insufficient. We are not aware of any attempt to observe Cir X-1 in the VHE γ-rays near its radio peaks.

Magnetic field differences?

Assuming that the total kinetic luminosity injected into the jet is proportional to the black hole mass, and that this is injected on a timescale proportional to the black hole mass, and that the magnetic field is in equipartition with the particle energy, then the magnetic field should be proportional to $M^{-0.5}$. A higher magnetic field means that (1) the synchrotron component will be stronger relative to the Compton component of the jet spectrum and (2) as discussed in the context of the Markoff et al. (2003) model for GX 339-4, even given synchrotron X-rays, the

particle energies will not need to be as high, and there may not be TeV electrons present.

Poorer observational coverage?

It is rather difficult to assess the role played by different observational strategies in studying AGN and X-ray binaries. Most of the VHE $\gamma-$ray observatories have pointed instruments which observe only a small field of view. The notable exception is MILAGRO, which has a much poorer sensitivity than the other instruments (although it might be sufficient for detecting a highly beamed event at high instrinsic luminosity from a nearby part of the Galaxy). This underscores the importance of publishing detailed upper limits including the times when the observations were made.

Conclusions

We have provided a brief overview of the X-ray and γ-ray emission from X-ray binaries with jets – also known as 'microquasars'. X-ray emission is unambiguously associated with jet-ISM interactions following major transient outbursts. It is certainly strongly coupled to the jet in steady states, although the nature of the coupling and the site of emission of the X-rays is not conclusively established. There are stong reasons, both directly from observations and by analogy with active galactic nuclei, that high energy γ-ray emission may also be associated with microquasars, particularly from those sources with jets inclined close to our line of sight ('microblazars'). New γ-ray observatories may well find X-ray binaries to be an important contributor to the γ-ray emission and particle acceleration within our Galaxy.

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